



# Modelling Nitrogen Flows in Agriculture and the Food Industry

A Focus on Nitrogen Flows and Budgets in Germany

Johannes große Macke  
Domhof 4a  
49074 Osnabrück  
+49 151 5224 5870  
[jgm@dil-ev.de](mailto:jgm@dil-ev.de)

# Contents

|                                                                                                            |           |
|------------------------------------------------------------------------------------------------------------|-----------|
| <b>1 Literature Review</b>                                                                                 | <b>3</b>  |
| 1.1 Global nitrogen reservoirs and cycle . . . . .                                                         | 4         |
| 1.2 The role of agriculture . . . . .                                                                      | 4         |
| 1.3 The role of food production and processing . . . . .                                                   | 5         |
| 1.4 Studies on nitrogen cycles in Germany . . . . .                                                        | 5         |
| 1.5 Potential measures to reduce nitrogen emissions from agriculture and food production systems . . . . . | 5         |
| <b>2 Next steps</b>                                                                                        | <b>6</b>  |
| <b>3 =====Outdated/Old versions=====</b>                                                                   | <b>8</b>  |
| <b>4 Introduction</b>                                                                                      | <b>8</b>  |
| 4.1 Research Gap . . . . .                                                                                 | 8         |
| <b>5 Current state of research in Germany</b>                                                              | <b>9</b>  |
| 5.1 Nitrogen losses in the food chain . . . . .                                                            | 9         |
| 5.2 Material Flows in the Food Industry of Germany . . . . .                                               | 10        |
| <b>6 Methodology: Nutrient Flows in the Food Industry: A Review of Methodologies</b>                       | <b>12</b> |
| 6.1 Introduction . . . . .                                                                                 | 12        |
| 6.2 Substance Flow Analysis and Material Flow Analysis . . . . .                                           | 12        |
| 6.2.1 Methodological Steps . . . . .                                                                       | 12        |
| 6.3 Software Tools . . . . .                                                                               | 13        |
| 6.4 Choosing the Appropriate Methodology . . . . .                                                         | 13        |
| 6.5 Conclusion . . . . .                                                                                   | 13        |
| 6.6 Other Models . . . . .                                                                                 | 13        |
| 6.6.1 CAPRI . . . . .                                                                                      | 13        |
| 6.6.2 MITERRA . . . . .                                                                                    | 14        |
| 6.7 Methodology for this research paper . . . . .                                                          | 14        |
| <b>7 Datasets</b>                                                                                          | <b>15</b> |
| 7.1 Data to be used for paper . . . . .                                                                    | 16        |
| 7.2 limitations . . . . .                                                                                  | 17        |

# 1 Literature Review

Nitrogen is the fourth most abundant element on Earth. It is also one of the six essential elements, which are summarised under the term CHNOPS, based on their respective elemental symbols. The element is an essential compound of organic life on Earth as well as the most common compound of the Earth's atmosphere (78 % V/V). However, only a small group of microbes is capable of metabolising pure Nitrogen into chemical combinations of different oxidation states metabolizable by other organisms [11]. For the most part of human history, the nitrogen cycle was balanced with little reactive N species accumulated in the environment, as metabolizable combinations were either sedimented or converted back to N<sub>2</sub> through denitrification. Thus Nitrogen was a limiting factor for the productive potential of ecosystem, while agriculture had to resort to crop rotation or manure or later the use of guano to increase crop productivity [29].

However both the industrial revolution starting in the 18th century as well as the agricultural revolutions of the last two hundred years and particularly the third agricultural revolution after the second world war, have resulted in large scale increase of the amount of reactive nitrogen species in the atmosphere as well as in terrestrial and aquatic ecosystems causing negative impacts from the point of view of sustainability as well as human health [19]. This paper intends to present results on nitrogen flows related to the food chain, starting, which involves crop and livestock production, food processing and eventually households. A similar study has been carried out for China more than a decade ago [30].

To the authors' knowledge such a study focussing on Germany has not been presented before and as such there exists a research gap. ~~In addition, while studies on nitrogen flow at national level have been presented for Germany (Häußermann et al., 2021), the study presented in this paper aims to develop a model of regional differentiation between German states, as climatic and topographic conditions, historical developments as well as different economical situations may have resulted in a differentiated development of agricultural production, food processing as well as household consumption.~~ Given Germany's position as second largest agricultural producer in Europe (BLE, 2023), nitrogen regime in Germany is also of high relevance at a European level. As Germany is both an important exporter as well as importer of agricultural products, animal feed and foodstuff, material flows caused by international trade also have to be considered in the study. **Comment Ioannis: I like the idea to focus more on processing and household consumption, as they are more relevant**

This work highlights the impacts of nitrogen flows within the German agricultural and food industry system and also identifies the most important negative ecological, social and economic impacts of this material flows. Results show that in order to optimize nitrogen regime within the food production system, collaboration is needed between farmers, food manufacturers and retailers as well as policy makers.

Following this introduction, the current state of research will be presented based on a review of previous work. In the following sections, materials and methods will be introduced, and results presented. A discussion will highlight the meaning of results in the context of previous work. In the concluding section implications of results for the agriculture and food sector in Germany will be

shown and potential future strategies for policy makers will be highlighted.

## 1.1 Global nitrogen reservoirs and cycle

The largest nitrogen reservoir on Earth is atmospheric nitrogen as  $N_2$ , which amounts to  $4.0 \times 10^9$  Tg. This is followed by Nitrogen in Oceans, mostly in the form of  $NO_3^-$ , amounting to  $6.6 \times 10^5$  Tg. There is also a geological reservoir of Nitrogen in other forms than  $N_2$  of an amount of about  $2.1 \times 10^9$  Tg. In terrestrial water  $1.0 \times 10^4$  Tg is held in groundwater resources, whereas a comparatively low amount of 42 Tg of Nitrogen is in terrestrial surface waters. Further reservoirs are in terrestrial soil to the amount of  $8.1 \times 10^4$  Tg and coastal sediments of  $3.2 \times 10^4$  Tg. The other two major reservoirs are terrestrial biosphere with  $1.4 \times 10^4$  Tg and marine biomass of  $1.8 \times 10^3$  Tg [43]. **Comment Ioannis: Numbers on 2.1 - cross-reference or comparison with Galloway 2004 since he has the same reservoirs**

Atmospheric  $N_2$  is fixated by microorganisms' (Archea and Bacteria) metabolism to ammonia ( $NH_3$ ). Through nitrification  $NH_3$  is then transformed to nitrite ( $NO_2^-$ ) and from nitrite to nitrate ( $NO_3^-$ ). Some microorganisms can also perform both reactions, these are called Complete Ammonia Oxidiser (COMAMOX).  $NH_3$  can also directly assimilated in  $NH_2$  groups of proteins in anoxic and oxic environments.  $NO_3^-$  is either reduced directly to  $NH_3$  through dissimilative reduction to ammonia (DNRA) or alternatively reduced to  $NO_2^-$  and then further reduced to gaseous N compounds (e.g.  $NO_2$ ,  $N_2O$ ) or directly to  $N_2$ . Also, in Anaerobic Ammonium Oxidation (ANAMOX)  $NO_2^-$  and  $NH_3$  are transformed into  $N_2$  and  $H_2O$  [11].

Anthropogenic fixation of  $N_2$  into reactive chemical compounds is caused by  $N_2$  fixation of agricultural crops (i.e. by symbiotic microorganisms of e.g. leguminous plants), industrial  $N_2$ -fixation mostly through the Haber-Bosch reaction and fossil fuel combustion. The latter produces  $NO_x$  and  $NH_y$  compounds, which are deposited into terrestrial and terrestrial waters and the oceans (either directly or influx from rivers) but also emitted from these into the atmosphere. **Comment Ioannis: Since N fixing symbiotic microorganisms are mentioned, might be nice to feature a small section on some biotechnology efforts to take advantage of other organisms to fix nitrogen or make mycorrhizal systems more productive.**

Release of  $N_2$  into the atmosphere is linked to ANAMOX processes, lead to release of  $N_2$  into the atmosphere. Natural processes are the biological fixation of  $N_2$  through microorganisms on land and in the oceans, the production of  $NO_x$  and  $NH_y$  caused by lightning, the disposition of these compounds into terrestrial and aquatic ecosystems and denitrification and ANAMOX processes caused by biological processes both on land and in waters [43].

## 1.2 The role of agriculture

Since the 1960s crop nitrogen budgets have increased from 40 Tg N/year to 151 Tg N/year in 2010. Most of this is considered to be due to more intensive farming practices and only to a lower extent (17 %) to an increase in arable land. The largest share of this is input in the form of industrial fertilizer, amount to 94 Tg N/year, followed by agricultural biological nitrogen fixation, amounting

to 27 Tg N/year, the use of manure as fertilizer at the level of 22 Tg N/year and deposition at the level of 16 Tg N/year. Compared to the nitrogen inputs, nitrogen removed from agricultural systems through crop harvest amounts only to 78 Tg N/year, resulting in a nitrogen surplus of 86 Tg N/year. Some of this surplus is released into the atmosphere through volatilization and emission or other forms of outputs, some of this is leaching into the soil and / or removed through surface runoff [42]. These figures relate to crop production only. **Comment Ioannis: Section 2.2: on crop production, I think that's the best paper to use, but maybe make a small remark saying how many datasets they analyzed**

Regarding animal production a study by [36] found that the majority of N-emissions into the environment result from manure spreading and synthetic fertilizer application, resulting in 44 Tg N/ year. The management of manure during animal production results in 12,4 Tg N/year. Both feed production as well as animal production cause emissions due to run-off and leaching at the levels of 23,9 Tg N/year for feed production and 4,2 Tg N/year for animal production. Annually 10.1 Tg N/year are used as input for the processing of livestock products (mostly meat, but also byproducts such as hides and skins). 0,9 Tg N/year are released into wastewater from processing industries, whereas 9,2 Tg N/year are delivered to consumers. Some of this is re-used as swill in animal production, although many countries have instigated legislation prohibiting this practice due to hygienic concerns and the fear of outbreaks of animal diseases in this context (Uwizeye et al., 2020).

Globally, there are regional differences as regards nitrogen emissions from animal production. The largest amount of 23 Tg N/year is emitted in South Asia, followed by East and Southeast Asia (18 Tg N/year) and Latin America and the Caribbean (7 Tg N/year). The very high levels in South Asia is due to large livestock populations (buffalo and cattle) managed at low productivity levels. In North America, Latin America and the Caribbean dairy cattle production causes 72% of all nitrogen emissions. Cattle production is the most relevant contribution to nitrogen emissions in the Middle East, North Africa and Sub-Saharan Africa, whereas in Europe pigs and cattle are the main causes.

**Comment Ioannis: since you have already a lot on animal NUE, you could add the figures from the paper titled "Livestock: on our plates or eating on our table" on what feed competes with food and what not. There's a whole report from FAO based solely on this paper, so I assume it's very solid**

### **1.3 The role of food production and processing**

### **1.4 Studies on nitrogen cycles in Germany**

### **1.5 Potential measures to reduce nitrogen emissions from agriculture and food production systems**

## 2 Next steps

1. Finish Literature Review
2. Choose research Directon
  - (a) test
3. Contact Prof. Dr. Silke Hüttel (h-index: 19) - Georg-August-Universität Göttingen, Department für Agrarökonomie und Rurale Entwicklung

OLD VERSION

### 3 =====Outdated/Old versions=====

## 4 Introduction

This paper offers a comprehensive investigation of the nitrogen cycle in agricultural systems, with a particular focus on nitrogen flows in Germany, and its impact on the food industry. The authors explore the intricate relationship between nitrogen use in agriculture, food production, and environmental sustainability, emphasizing the importance of efficient nitrogen management for the future of food security both locally and globally.

The paper starts by describing the essential role of nitrogen in plant growth and the primary sources of nitrogen in agriculture, which include synthetic fertilizers, animal manure, and biological nitrogen fixation. The authors delve into the benefits of nitrogen application in enhancing crop yields, as well as the challenges it poses for environmental sustainability, particularly in terms of water pollution, greenhouse gas emissions, and soil degradation [17, 22].

The authors then provide an in-depth analysis of nitrogen flows in Germany, showcasing how the country's agricultural practices contribute to the nitrogen cycle. They highlight that Germany's intensive farming practices have led to a significant increase in nitrogen inputs, which have caused environmental problems such as eutrophication, nitrate leaching, and ammonia emissions [26, 31]. Furthermore, they point out that Germany's food system is deeply intertwined with its nitrogen flows, as the country relies on imports of animal feed, resulting in substantial nitrogen imbalances.

To optimize nitrogen use in agricultural systems, the paper discusses various strategies, such as precision farming, crop rotation, and the use of cover crops [41, 24]. These methods aim to minimize the negative environmental impacts of nitrogen application while maintaining or increasing crop yields. In the case of Germany, the authors suggest implementing region-specific strategies to address the unique challenges posed by local farming practices and environmental conditions.

In the food industry, the authors stress the importance of reducing nitrogen losses in the food supply chain and adopting sustainable practices, such as waste reduction, recycling of organic materials, and the promotion of plant-based diets [6, 40]. They also highlight the need for collaboration among German farmers, food manufacturers, retailers, and policymakers in creating a more sustainable food system that can serve as a model for other countries.

Finally, the paper concludes by underscoring the necessity for a global effort to address the challenges posed by nitrogen use in agriculture and the food industry, as well as the need for continued research and innovation in this field. The authors advocate for international cooperation in sharing best practices and lessons learned from Germany's experience in managing nitrogen flows to promote environmental sustainability and food security worldwide.

### 4.1 Research Gap

The investigation of nitrogen cycles within the food industry remains a relatively unexplored domain in research, despite its potential implications for environmental sustainability and resource management. Existing literature has primarily focused on nitrogen dynamics in agricultural sys-



tems [17, 34], yet a comprehensive analysis addressing the complexities and interconnections of nitrogen flows throughout the food production, processing, distribution, and consumption stages is conspicuously absent. By addressing this research gap, we stand to gain critical insights into the optimization of resource use, the minimization of nitrogen-related environmental impacts, and the identification of innovative strategies for fostering sustainable food systems. Furthermore, an in-depth understanding of nitrogen cycles in the food industry can inform policy development and guide industry practices, ultimately contributing to global efforts in mitigating the adverse effects of nitrogen pollution on ecosystems and human health [5].

## **5 Current state of research in Germany**

Several studies have investigated the magnitude and sources of nitrogen losses along the food chain in Germany. Leip et al. [26] found that nitrogen losses occur at various stages, from agricultural production to consumption, including leaching, runoff, ammonia volatilization, and nitrous oxide emissions. In crop production, nitrogen losses primarily stem from excessive and imprecise application of nitrogen fertilizers, while in livestock production, manure management and emissions from animal housing systems contribute to the losses [26, 31].

Erisman et al. [10] highlighted the environmental and human health impacts of nitrogen losses, including eutrophication, soil acidification, and air pollution. They emphasized the importance of adopting an integrated approach to address the complex issue of nitrogen losses and their environmental consequences.

Potential mitigation strategies for reducing nitrogen losses in the German food chain have been explored, such as improving nitrogen use efficiency in agricultural production, optimizing manure management, implementing precision farming techniques, and promoting sustainable consumption patterns [31, 26]. Researchers have also suggested the need for multi-sectoral approaches, including policy measures and technological innovations, to comprehensively address nitrogen losses [26, 10].

Despite the extensive research on nitrogen losses in the food chain, several areas still require further investigation. There is a need to monitor and evaluate the effectiveness of proposed mitigation strategies and identify additional measures for reducing nitrogen losses [31]. Further research is also required to improve the understanding of nitrogen dynamics in the food chain, particularly in the context of changing agricultural practices, land-use patterns, and climate change [26, 10]. Moreover, interdisciplinary research is necessary to better understand the interactions between nitrogen losses and other environmental challenges, such as greenhouse gas emissions and biodiversity loss [10].

### **5.1 Nitrogen losses in the food chain**

Nitrogen losses in the food chain occur at various stages, from agricultural production to food consumption and waste disposal. These losses can have significant environmental and health impacts.

The following elaboration on nitrogen losses along the food chain highlights the primary sources of loss and their implications:

1. **Agricultural production:** During agricultural production, nitrogen losses occur primarily through ammonia volatilization, nitrate leaching, nitrous oxide emissions, and nitrogen runoff [26]. Factors such as fertilizer application rates, timing and method of application, soil type, crop type, and weather conditions influence the extent of nitrogen losses at this stage [35]. In Germany, a considerable portion of applied nitrogen is lost to the environment, with estimates ranging from 20 to 50% [31].
2. **Livestock production:** Livestock farming also contributes to nitrogen losses, as manure generated by animals contains nitrogen that can be lost through volatilization, leaching, or runoff when the manure is applied to agricultural land [26]. Intensive livestock systems, such as pig and poultry farming, often generate large amounts of manure, increasing the risk of nitrogen losses.
3. **Food processing and transportation:** During food processing and transportation, nitrogen losses can occur as a result of ammonia emissions from refrigeration systems, nitrogen compounds released during food processing (e.g., nitrous oxide from the production of nitric acid), and nitrogen leaching during wastewater treatment [10].
4. **Food consumption and waste:** Household food waste and human excretion contribute to nitrogen losses in the food chain [37]. The disposal of food waste in landfills can lead to the release of ammonia and nitrous oxide, while wastewater treatment plants can discharge nitrogen compounds into water bodies, contributing to eutrophication and water pollution.

In conclusion, research on nitrogen losses along the food chain in Germany has provided valuable insights into the magnitude, sources, and potential mitigation strategies for addressing this pressing environmental issue. Further research is needed to advance our understanding of nitrogen dynamics, monitor the effectiveness of mitigation measures, and develop integrated approaches to promote sustainable agriculture and environmental management.

## **5.2 Material Flows in the Food Industry of Germany**

In this chapter, we present a comprehensive analysis of the most significant material flows within the German food industry, investigating their interrelations with nitrogen cycles and their impact on the environment. By examining material flows, such as cereals, potatoes, sugar beets, oilseeds, fruits and vegetables, milk and dairy products, beef and pork, poultry, fish and seafood, and beverages, we aim to elucidate the current state of research in this domain. Understanding these interdependencies is crucial for identifying potential areas of optimization, informing policy decisions, and guiding the industry towards more sustainable practices. Additionally, this analysis contributes to the broader scientific literature on nitrogen cycles, emphasizing the importance of incorporating industry-specific perspectives to achieve a holistic understanding of the environmental implications of the German food industry.

1. Cereals: Germany produces a substantial amount of cereals, predominantly wheat, barley, and rye. These cereals serve as the foundation for numerous food products, including bread, pasta, and baked goods.
2. Potatoes: The German food industry heavily relies on potato production, which is utilized for a wide array of products, such as potato chips, mashed potatoes, and various potato-based dishes.
3. Sugar beets: Germany holds a significant position in sugar beet production, with the crop being processed into sugar and other related products like syrups and molasses.
4. Oilseeds: The primary oilseeds produced in Germany include rapeseed and sunflower seeds, which are processed into vegetable oils and meal for animal feed.
5. Fruits and vegetables: The German food industry cultivates various fruits and vegetables for both local consumption and export. Common fruits encompass apples, cherries, and strawberries, while prevalent vegetables include carrots, onions, and cabbage.
6. Milk and dairy products: As one of the largest dairy producers in the European Union, Germany's milk production is vital for creating a variety
7. Milk and dairy products: As one of the largest dairy producers in the European Union, Germany's milk production is vital for creating a variety
8. Beef and pork: Germany holds a significant position in beef and pork production, which are utilized in a diverse range of food products, such as sausages, cold cuts, and processed meat products.
9. Poultry: The German food industry is a major producer of poultry, particularly chicken and turkey. Poultry is used in various food products, including deli meats, sausages, and prepared dishes.
10. Fish and seafood: While not as prominent as other material flows, Germany maintains a fishing industry that focuses on both freshwater and marine fish, including herring, mackerel, and trout. Aquaculture also contributes to the production of fish and seafood, such as carp and shellfish.
11. Beverages: Germany boasts a robust beverage industry, encompassing the production of beer, wine, and a variety of non-alcoholic beverages, such as fruit juices, mineral water, and soft drinks.

In conclusion, by examining these significant material flows within the German food industry and their interrelations with nitrogen cycles, we provide a foundation for further research and foster a better understanding of the environmental impacts associated with food production.

## 6 Methodology: Nutrient Flows in the Food Industry: A Review of Methodologies

### 6.1 Introduction

Understanding nutrient flows within the food industry is essential for addressing the complex challenges of resource use efficiency, environmental sustainability, and food security [17]. Accurate quantification and analysis of nutrient flows can inform policy decisions and guide the industry towards more sustainable practices [2]. This chapter reviews the methodologies commonly employed for determining nutrient flows in the food industry, with a focus on Substance Flow Analysis (SFA) and Material Flow Analysis (MFA), and provides guidance on their application.

### 6.2 Substance Flow Analysis and Material Flow Analysis

Substance Flow Analysis (SFA) and Material Flow Analysis (MFA) are widely used methodologies for studying nutrient flows and resource use in various industries, including the food sector [32, 8]. While SFA focuses on tracking the flow of specific substances (e.g., nitrogen or phosphorus) within a defined system, MFA tracks the flow of materials (e.g., crops, livestock products, and feed) through different stages of the food system.

#### 6.2.1 Methodological Steps

Conducting an SFA or MFA for the food industry typically involves the following steps [1]:

1. *Define the system boundaries:* Clearly outline the scope of the analysis, including the specific food products, supply chain stages, and geographical boundaries being considered.
2. *Identify key data sources:* Collect data on production, consumption, trade, and waste management for the food products and nutrients of interest. This may include national statistics, industry reports, and scientific literature.
3. *Calculate material and nutrient flows:* Using the collected data, calculate the inputs, outputs, and transformations of materials and nutrients at each stage of the food system. This may involve the use of mass balance equations, conversion factors, and allocation rules.
4. *Visualize and interpret the results:* Create flow diagrams, Sankey diagrams, or other visualizations to help understand the patterns and relationships between different components of the food system. Interpret the results in the context of sustainability goals, policy implications, and potential interventions.
5. *Assess the uncertainties and limitations:* Evaluate the uncertainties and limitations associated with the data sources, assumptions, and methods used in the analysis, and consider conducting sensitivity analyses to assess the robustness of the results.

### **6.3 Software Tools**

Several software tools can be used to support the SFA and MFA process, including STAN (SubSTance Flow ANALysis software) [7] and OpenLCA [9]. These tools facilitate data management, calculations, and visualization of nutrient flows within the food system.

### **6.4 Choosing the Appropriate Methodology**

The choice of methodology depends on the specific research question, data availability, and the scale of the analysis. In some cases, more complex models like MITERRA [38] or CAPRI [3] may be required to analyze nutrient flows in the context of specific policy interventions or environmental impacts. However, for most studies examining nutrient flows within the food industry, SFA and MFA provide a robust and flexible framework for capturing the essential dynamics of material and nutrient flows across various stages of the food system.

### **6.5 Conclusion**

Accurate quantification and analysis of nutrient flows within the food industry are crucial for guiding policy decisions and promoting sustainable practices [18]. SFA and MFA are valuable methodologies for studying nutrient flows and resource use in the food sector, providing a comprehensive understanding of the flow of materials and nutrients within the food system, from production to consumption and waste management [28]. By selecting the appropriate methodology and following the outlined methodological steps, researchers can gain valuable insights into the environmental implications of the food industry and identify opportunities for optimizing resource use, reducing environmental impacts, and promoting more sustainable practices throughout the entire supply chain [23].

### **6.6 Other Models**

This scientific paper provides a comprehensive comparison of the Common Agricultural Policy Regionalized Impact (CAPRI) model [4] and the MITigation of Environmental impact of Trans-boundary Agro-ecosystems through Regional Analysis (MITERRA) model [39], highlighting their respective advantages and disadvantages in assessing agricultural nitrogen flows and environmental impacts. Both models serve as important tools for simulating agricultural production, land use, and environmental impacts, aiding policymakers in decision-making processes related to sustainable agriculture and environmental management.

#### **6.6.1 CAPRI**

The CAPRI model is an economic and environmental model focused on European agriculture, developed to analyze the effects of Common Agricultural Policy (CAP) reforms and trade liberalization on agricultural production, income, land use, and environmental indicators [4]. Advantages of the

CAPRI model include its detailed regional representation, capturing the heterogeneity of agricultural production systems across Europe [26], its ability to assess policy measures on agricultural markets and income, land use, and nitrogen flows, and its incorporation of extensive databases, including biophysical and socioeconomic data, enhancing its reliability and accuracy. However, disadvantages of the CAPRI model involve its focus on European agriculture, which may limit its applicability to other regions, its complexity and data requirements that may hinder its accessibility for certain users, and its potential lack of ability to simulate some specific management practices, which could affect the accuracy of its environmental impact assessments [4].

### **6.6.2 MITERRA**

On the other hand, the MITERRA model is a deterministic, static, and spatially explicit model designed to assess the environmental impacts of agricultural production across Europe, including nitrogen flows, greenhouse gas emissions, and ammonia emissions [39]. Advantages of the MITERRA model encompass its coverage of a wide range of environmental indicators, providing a comprehensive assessment of the environmental impacts of agriculture, its relative simplicity and user-friendly nature, making it accessible to a broader range of users, and its ease of being updated and adapted to incorporate new data, methods, or policy measures [39]. Conversely, disadvantages of the MITERRA model include its simplicity and static nature, which may limit its ability to capture the complexities of agricultural systems and the dynamic nature of agricultural policies, its lack of direct accounting for economic factors or the effects of policy measures on agricultural markets and income, and its focus on European agriculture, which may limit its applicability to other regions [39].

In conclusion, both CAPRI and MITERRA models offer valuable insights into agricultural nitrogen flows and environmental impacts. While CAPRI provides a more detailed regional representation and incorporates economic factors, MITERRA offers a simpler, more accessible approach. Decision-makers should consider the strengths and limitations of each model to select the most appropriate tool for their specific needs and objectives.

## **6.7 Methodology for this research paper**

The methodology of this study encompasses the processing and utilization of various datasets, literature sources, and computations. An exhaustive breakdown of the data sources and processing techniques is as follows:

Groups were identified based on the Definitions and standards of the Food and Agriculture Organization (FAO) Food Balances (2010-), specifically within the "Item group" section [12].

Categories were allocated according to the "Item description" from the same FAO document. It is noteworthy that each Category contains numerous Items, termed "FBS Items" for the purposes of this study [12].

Data regarding Supply Utilization Accounts (SUA) Items were obtained from the FAO Supply

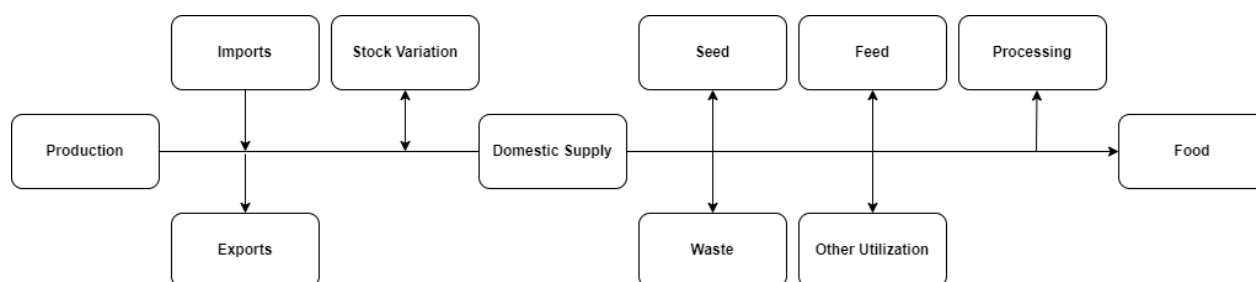


Figure 1: Data Flow of FAO Information; Own representation based on FAO

Utilization Accounts (2010-) Definitions and standards, particularly the "Item Description" section [13]. SUA Items were matched to FBS Items by employing the Item Codes from both documents. Despite minor variations in Item names, this method ensured that SUA Items were categorized according to the FAO Food Balances (2010-) Definitions and Standards [12].

Information pertaining to Item Code and CPC Code was also sourced from the FAO Supply Utilization Accounts (2010-) Definitions and standards, within the "Item Description" section [13]. Data on Calories, Proteins, Fats, and Carbs were referenced from the FAO Nutritive Factors document.

Nitrogen Factors were derived from the latest relevant literature and applied at the Category level. The principal source was [15]. For items lacking a specific factor, a default factor of 5.6 was used, derived as an average of both animal and plant products by the study. For vegetables, [16] "Nitrogen to Protein Conversion Factors for Common Vegetables in Japan" was referenced, and 4.39 was used as an appropriate factor.

Data elements related to Production, Import Quantity, Opening Stocks, Stock Variation, Export Quantity, Feed, Seed, Loss, Other uses (non-food), Processed, Proteins/Year, Calories/Year, Fat supply quantity (g/capita/day), Fats/Year, Food supply (kcal/capita/day), and Food supply quantity (g/capita/day), Protein supply quantity (g/capita/day) were gathered from the FAOSTAT Database, specifically the Supply Utilization Accounts (2010-) dataset [13].

Values for Protein Production, Protein Import Quantity, Protein Opening Stocks, Protein Stock Variation, Protein Export Quantity, Protein Feed, Protein Seed, Protein Loss, Protein Other uses (non-food), and Protein Processed were computed by multiplying each metric column with the Proteins column. Similarly, Nitrogen Production, Nitrogen Import Quantity, Nitrogen Opening Stocks, Nitrogen Stock Variation, Nitrogen Export Quantity, Nitrogen Feed, Nitrogen Seed, Nitrogen Loss, Nitrogen Other uses (non-food), Nitrogen Food Supply, Nitrogen Processed, and Nitrogen/Year Food were computed by multiplying each Protein metric column with the Nitrogen Factor column.

Finally, estimates of waste percentage for each category involved were derived from [20].

## 7 Datasets

To conduct a comprehensive analysis of the German food system with respect to nitrogen cycles, it is essential to collect data from multiple dimensions, including production, consumption, and nitrogen contents. The following types of data are required for an in-depth investigation:

- Production data: Information on the production volumes, areas cultivated, and yields of various crops (cereals, potatoes, sugar beets, oilseeds, fruits, and vegetables), as well as live-stock (beef, pork, poultry, and dairy) and fisheries (freshwater, marine, and aquaculture). This data should encompass both national and regional levels to account for variations in agricultural practices and environmental conditions [14].
- Consumption data: Detailed data on consumption patterns of various food items, encompassing quantities, frequencies, and preferences of the population. This information should be disaggregated by demographic factors, such as age, gender, and socioeconomic status, to capture the diversity of dietary habits within the country [33].
- Nitrogen contents: Comprehensive data on the nitrogen content of various food products, agricultural inputs (e.g., fertilizers, manure), and crop residues. This information is crucial for understanding the dynamics of nitrogen flows within the food system and their implications for environmental impacts [27].
- Supply chain data: Information on the structure and organization of the food supply chain, including the relationships between producers, processors, distributors, retailers, and consumers. This data is vital for understanding the flow of nitrogen-containing materials through the food system and pinpointing potential areas for intervention and intervention and optimization [18].
  - Feed In order to thoroughly analyze the nitrogen cycles within the German food system, it is crucial to consider the role of animal feed, as it contributes significantly to nitrogen flows within the system. Data on the following aspects is essential for a comprehensive understanding:
    - \* Feed composition: Gathering information on the types and quantities of feed ingredients (e.g., cereals, oilseed meals, and forage) used for different livestock species, as well as the nitrogen content of these feedstuffs, is vital for estimating nitrogen intake by animals and its distribution within the system [25].
    - \* Feed import and export: Collecting data on the import and export of animal feed and feed ingredients can impact the overall nitrogen balance within the country. Both the quantity and nitrogen content of the imported and exported feed materials should be considered, as these transactions represent a transfer of nitrogen across borders [2].
    - \* Animal nitrogen utilization efficiency: Acquiring information on the efficiency with which animals convert ingested nitrogen into protein products (e.g., meat, milk, eggs) is important, as not all nitrogen consumed by animals is retained in the form of protein. A portion of the ingested nitrogen is excreted as waste, contributing to environmental pollution if not managed properly [34].



| Food Group |              | Food Item                         | Consumption (kg food/capita/yr) | Caloric Consumption (kcal/capita/yr) | Protein Consumption (g/capita/day) | Fat Consumption (g/capita/day) |
|------------|--------------|-----------------------------------|---------------------------------|--------------------------------------|------------------------------------|--------------------------------|
| Meat       | Ruminant     | Bovine meat                       | 14,79                           | 43                                   | 5,3                                | 2,31                           |
|            |              | Mutton and goat meat              | 0,82                            | 5                                    | 0,28                               | 0,45                           |
|            |              | Pig meat                          | 43,2                            | 200                                  | 11,89                              | 16,54                          |
|            | Non-ruminant | Poultry meat                      | 18,15                           | 67                                   | 7,43                               | 3,92                           |
|            |              | Meat, other                       | 1,79                            | 5                                    | 0,98                               | 0,13                           |
|            |              | Offals, edible                    | 1,69                            | 6                                    | 0,92                               | 0,17                           |
| Seafood    |              | Freshwater fish                   | 4,39                            | 8                                    | 1,2                                | 0,28                           |
|            |              | Demersal fish                     | 3,93                            | 20                                   | 1,82                               | 1,37                           |
|            |              | Pelagic fish                      | 2,47                            | 7                                    | 0,78                               | 0,37                           |
|            |              | Marine fish, other                | 0,36                            | 1                                    | 0,13                               | 0,03                           |
|            |              | Crustaceans                       | 0,88                            | 1                                    | 0,22                               | 0,01                           |
|            |              | Cephalopods                       | 0,26                            | 1                                    | 0,1                                | 0,01                           |
|            |              | Molluscs, other                   | 0,38                            | 0                                    | 0,03                               | 0                              |
|            |              | Aquatic animals, others           | 0,02                            | 0                                    | 0                                  | 0                              |
|            |              |                                   |                                 |                                      |                                    |                                |
| Dairy      |              | Cream                             | 6,71                            | 36                                   | 0,5                                | 3,55                           |
|            |              | Butter, ghee                      | 6,12                            | 120                                  | 0,15                               | 13,59                          |
|            |              | Milk (excluding butter) *includes | 171,04                          | 383                                  | 28,11                              | 19,86                          |
| Eggs       |              | Eggs                              | 13,21                           | 52                                   | 4,18                               | 3,63                           |
|            |              | Oilcrops, other                   | 0,11                            | 2                                    | 0,05                               | 0,13                           |
| Oils       |              | Soybean oil                       | 5,09                            | 123                                  | 0                                  | 13,94                          |
|            |              | Groundnut oil                     | 0,02                            | 0                                    | 0                                  | 0,04                           |
|            |              | Sunflowerseed oil                 | 4,02                            | 100                                  | 0                                  | 11,29                          |
|            |              | Rape and mustard oil              | 5,15                            | 134                                  | 0,01                               | 15,1                           |
|            |              | Cottonseed oil                    | 0                               | 0,0                                  | 0,0                                | 0,0                            |
|            |              | Palmkernel oil                    | 0                               | 0,0                                  | 0,0                                | 0,0                            |
|            |              | Sesame seed oil                   | 0                               | 2                                    | 0                                  | 0,24                           |
|            |              | Palm oil                          | 0                               | 41                                   | 0,03                               | 4,65                           |
|            |              | Coconut oil                       | 0                               | 30                                   | 0,02                               | 3,35                           |
|            |              | Olive Oil                         | 0,75                            | 18                                   | 0                                  | 2,06                           |
|            |              | Rice bran oil                     | 0                               | 0,0                                  | 0,0                                | 0,0                            |
|            |              | Maize germ oil                    | 0,15                            | 4                                    | 0                                  | 0,42                           |
|            |              | Oilcrops oil, other               | 0,79                            | 16                                   | 0                                  | 1,88                           |
|            |              | Fats, animals, raw                | 0,06                            | 130                                  | 0,01                               | 14,43                          |
|            |              | Fish, body oil                    | 0                               | 0,0                                  | 0,0                                | 0,0                            |
|            |              | Fish, liver oil                   | 0                               | 0,0                                  | 0,0                                | 0,0                            |
|            |              | Sunflower seed                    | 0                               | 0,0                                  | 0,0                                | 0,0                            |
|            |              | Rape and mustardseed              | 0                               | 4                                    | 0                                  | 0                              |
|            |              | Sesame seed                       | 0                               | 0,0                                  | 0,0                                | 0,0                            |
|            |              | Palm kernels                      | 0                               | 0,0                                  | 0,0                                | 0,0                            |
|            |              | Olives (including preserved)      | 0,82                            | 2                                    | 0,02                               | 0,25                           |

Figure 2: Consumption and Proteincontent (Germany)

## 7.1 Data to be used for paper

The data is from the article "Future warming from global food consumption" and can be used to determine the consumption of different foods in germany as well as their protein content - and therefore the N-content [21]<sup>1</sup>

## 7.2 limitations

<sup>1</sup>See Mail Volker Heinz from 27.03.2023

## List of Figures

|   |                                                                         |    |
|---|-------------------------------------------------------------------------|----|
| 1 | Data Flow of FAO Information; Own representation based on FAO . . . . . | 15 |
| 2 | Consumption and Proteincontent (Germany) . . . . .                      | 17 |

## References

- [1] Peter Baccini and Paul H Brunner. *The metabolic of the anthroposphere*. Springer, 1991.
- [2] Alexander F Bouwman, Lex JM Boumans, and Niels H Batjes. Modeling global annual n<sub>2</sub>o and no emissions from fertilized fields. *Global Biogeochemical Cycles*, 16(4):28–1–28–9, 2002.
- [3] Wolfgang Britz and Peter Witzke. Capri model documentation 2008: Version 2. Technical report, Institute for Food and Resource Economics, University of Bonn, 2008.
- [4] Wolfgang Britz and Peter Witzke. Capri model documentation 2014, 2014.
- [5] Julio A Camargo and Alvaro Alonso. Nitrogen pollution in aquatic ecosystems. *Environmental Pollution*, 174:200–210, 2013.
- [6] Emily S Cassidy, Paul C West, James S Gerber, and Jonathan A Foley. Redefining agricultural yields: from tonnes to people nourished per hectare. *Environmental Research Letters*, 8(3):034015, 2013.
- [7] Michael Cerny, David Laner, and Helmut Rechberger. Stan: Substance flow analysis software. *Vienna University of Technology*, 2018.
- [8] Min Chen, Lin Ma, and B Chen. Substance flow analysis of phosphorus in china. *Resources, Conservation and Recycling*, 60:177–183, 2012.
- [9] Andreas Citroth, Gregor Fleischer, and Jan Steinbach. Ict for environment in life cycle applications openlca—a new open source software for life cycle assessment. *International Journal of Life Cycle Assessment*, 16(5):439–446, 2011.
- [10] Jan Willem Erisman, Mark A Sutton, James Galloway, Zbigniew Klimont, and Wilfried Winiwarter. How a century of ammonia synthesis changed the world. *Nature geoscience*, 1(10):636–639, 2008.
- [11] Massimiliano Fenice. The nitrogen cycle: An overview. *Nitrogen Cycle: Ecology, Biotechnological Applications and Environmental Impacts*, 22(1):1–21, 2021.
- [12] Food and Agriculture Organization of the United Nations. Fao food balances (2010-). <https://www.fao.org/faostat/en/data/FBS>.
- [13] Food and Agriculture Organization of the United Nations. Fao supply utilization accounts (2010-) definitions and standards. <https://www.fao.org/faostat/en/data/SCL>.

- [14] Food and Agriculture Organization of the United Nations. Faostat, 2021.
- [15] Philippe Patureau Mirand François Mariotti, Daniel D. Tomé. Converting nitrogen into protein – beyond 6.25 and Jones' factors. *Critical Reviews in Food Science and Nutrition*, 48(2):177–184, 2008.
- [16] S Fujihara, A Kasuga, and Y Aoyagi. Nitrogen-to-protein conversion factors for common vegetables in Japan. *Journal of Food Science*, 66(3):412–415, 2001.
- [17] James N Galloway, Alan R Townsend, Jan Willem Erisman, Mateete Bekunda, Zucong Cai, John R Freney, Luiz A Martinelli, Sybil P Seitzinger, and Mark A Sutton. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science*, 320(5878):889–892, 2008.
- [18] Jenny Gustavsson, Christel Cederberg, Ulf Sonesson, and Annika Emanuelsson. Global food losses and food waste. *Rapport*, 2011, 2011.
- [19] Ole Hertel, CA Skjøth, Stefan Reis, A Bleeker, RM Harrison, J Neil Cape, David Fowler, Ute Skiba, D Simpson, Timothy Jickells, et al. Governing processes for reactive nitrogen compounds in the European atmosphere. *Biogeosciences*, 9(12):4921–4954, 2012.
- [20] R. Herzberg, T.G. Schmidt, and F. Schneider. Characteristics and determinants of domestic food waste: A representative diary study across Germany. *Sustainability*, 12(4702), 2020.
- [21] Catherine C Ivanovich, Tianyi Sun, Doria R Gordon, and Ilissa B Ocko. Future warming from global food consumption. *Nature Climate Change*, pages 1–6, 2023.
- [22] Willem Erisman Jan, A Sutton Mark, Galloway James, Klimont Zbigniew, and Winiwarter Wilfried. How a century of ammonia synthesis changed the world. *Nature Geoscience*, 1(10):636–639, 2008.
- [23] Ling Jiang, Xinde Cao, and Qing Chen. Material flow analysis of phosphorus through food consumption in two megacities in northern China. *Ecological Indicators*, 48:96–103, 2015.
- [24] Xiao-Tang Ju, Guang-Xi Xing, Xin-Ping Chen, Shao-Lin Zhang, Li-Juan Zhang, Xue-Jun Liu, Zhen-Ling Cui, Bin Yin, Peter Christie, Zhao-Liang Zhu, et al. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences*, 106(9):3041–3046, 2009.
- [25] Olena Kalinina, Isabelle Baltenweck, and Alan J. Duncan. Animal feed and climate change: Impact of feed quality and forage on greenhouse gas emissions and animal performance. *CABI Agriculture and Bioscience*, 1:1–12, 2018.
- [26] Adrian Leip, Wolfgang Britz, Franz Weiss, and Wim de Vries. Farm, land, and soil nitrogen budgets for agriculture in Europe calculated with CAPRI. *Environmental Pollution*, 159(11):3243–3253, 2011.

- [27] Adrian Leip, Wolfgang Britz, Franz Weiss, and Wim de Vries. Farm, land, and soil nitrogen budgets for agriculture in europe calculated with capri. *Environmental Pollution*, 159(11):3243–3253, 2011.
- [28] Adrian Leip, Franz Weiss, Tom Wassenaar, Ignacio Perez, Thomas Fellmann, Philippe Loudjani, Francesco Tubiello, David Grandgirard, Suvi Monni, and Katarzyna Biala. Evaluation of the livestock sector’s contribution to the eu greenhouse gas emissions (ggels). *European Commission, Joint Research Centre*, 2011.
- [29] María López-Aizpún, Antonio Castellano-Hinojosa, Jesús González-López, Eulogio J Bedmar, Nadine Loick, Harry Barrat, Yan Ma, Dave Chadwick, and Laura M Cardenas. Nitrogen cycle in agriculture: biotic and abiotic factors regulating nitrogen losses. In *Nitrogen Cycle*, pages 34–59. CRC Press, 2021.
- [30] L Ma, WQ Ma, GL Velthof, FH Wang, W Qin, FS Zhang, and O Oenema. Modeling nutrient flows in the food chain of china. *Journal of environmental quality*, 39(4):1279–1289, 2010.
- [31] B. Osterburg, F.U. Weiß, and A Laggner. Nitrogen flows and balances at the national level: Indicators for the environmental impact of nitrogen in agriculture. *Landbauforschung Volkenrode*, 63(3):145–160, 2013.
- [32] Shweta Singh and Bhavik R Bakshi. Material flow analysis of fossil fuels in india during 1970–1971 and 1996–1997. *Energy*, 26(10):821–831, 2001.
- [33] Statistisches Bundesamt. Statistisches bundesamt (destatis), 2021.
- [34] Mark A. Sutton, Clare M. Howard, Jan Willem Erisman, Gilles Billen, Albert Bleeker, Perine Grennfelt, Hans van Grinsven, and Bruna Grizzetti, editors. *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives*. Cambridge University Press, 2011.
- [35] Mark A Sutton, Oene Oenema, Jan Willem Erisman, Adrian Leip, Hans van Grinsven, and Wilfried Winiwarter. Too much of a good thing. *Nature*, 472(7342):159–161, 2011.
- [36] Aimable Uwizeye, Imke JM de Boer, Carolyn I Opio, Rogier PO Schulte, Alessandra Falcucci, Giuseppe Tempio, Félix Teillard, Flavia Casu, Monica Rulli, James N Galloway, et al. Nitrogen emissions along global livestock supply chains. *Nature Food*, 1(7):437–446, 2020.
- [37] Hans JM Van Grinsven, Jan Willem Erisman, Wim De Vries, and Henk Westhoek. Potential of extensification of european agriculture for a more sustainable food system, focusing on nitrogen. *Environmental Research Letters*, 10(2):025002, 2015.
- [38] Gerard L Velthof, Diti Oudendag, H Peter Witzke, Willem A H Asman, Zbigniew Klimont, and Oene Oenema. An integrated assessment of nitrogen losses from agriculture in eu-27: Miterra-europe. *Journal of Environmental Quality*, 41(2):324–335, 2012.

- [39] GL Velthof, D Oudendag, HP Witzke, WAH Asman, Z Klimont, and O Oenema. Integrated assessment of nitrogen losses from agriculture in eu-27 using miterra-europe. *Journal of Environmental Quality*, 38(2):402–417, 2009.
- [40] Paul C West, James S Gerber, Peder M Engstrom, Nathaniel D Mueller, Kate A Brauman, Kimberly M Carlson, Emily S Cassidy, Matt Johnston, Graham K MacDonald, Deepak K Ray, et al. Leverage points for improving global food security and the environment. *Science*, 345(6194):325–328, 2014.
- [41] Xin Zhang, Eric A Davidson, Denise L Mauzerall, Timothy D Searchinger, Patrice Dumas, and Ye Shen. Managing nitrogen for sustainable development. *Nature*, 528(7580):51–59, 2015.
- [42] Xin Zhang, Tan Zou, Luis Lassaletta, Nathaniel D Mueller, Francesco N Tubiello, Matthew D Lisk, Chaoqun Lu, Richard T Conant, Christopher D Dorich, James Gerber, et al. Quantification of global and national nitrogen budgets for crop production. *Nature Food*, 2(7):529–540, 2021.
- [43] Xinning Zhang, Bess B Ward, and Daniel M Sigman. Global nitrogen cycle: critical enzymes, organisms, and processes for nitrogen budgets and dynamics. *Chemical reviews*, 120(12):5308–5351, 2020.